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THE STRENGTH AND ELASTICITY OF STRUCTURAL STEEL, AND ITS EFFICIENCY IN THE FORM OF BEAMS AND STRUTS.

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The various grades of steel used in structures possess such an extended range of physical properties, that it is impossible to consider the metal in its individual sense, as we might treat of iron.

The character of steel is so largely determined by the various agents that enter into its composition, that a complete description of any particular grade involves a consideration of these agents.

It is customary, however, to denominate each grade by the percentage of carbon it contains. As a general rule, the higher the carbon percentage, the higher the tenacity of the steel will be, and the lower its ductility.

The subjoined list exhibits the average tensile resistance and ductility of steels having the stated proportions of carbon :

PERCENTAGE OF CARBON.	TENACITY IN LBS. PER SQUARE INCH.		DUCTILITY.
	Ultimate.	Elastic Limit.	Ult. Elongation in 8 Inches.
.10	60 000	36 000	26 per cent.
.15	66 000	40 000	24 "
.20	74 000	45 000	22 "
.25	82 000	50 000	20 "
.30	90 000	55 000	18 "
.35	100 000	60 000	16 "
.40	110 000	65 000	14 "

These figures, however, are only approximate, as much depends on the quality of the steel and the reduction of its section by rolling from the ingot to the finished bar. Steel, whose carbon ratio is below or does not much exceed .15 per cent., is known conventionally as "mild" or "soft" steel.

Aside from its lower tensile strength and greater ductility, as compared with the harder steels, it is distinguished by its superior welding property, and also by its moderate hardening property when chilled in water from a red heat.

Steel having .10 to .12 per cent. of carbon should double flat without fracture, when chilled in cold water from a red heat. When the carbon ratio reaches .15 it should still bend around a curve whose diameter is three or four times the thickness of the specimen operated upon, and when chilled in water of 80° F. When the carbon ratio reaches .35 or .40 the steel will harden sufficiently to cut soft iron and maintain an edge.

The steels, which were subjected to the tests hereafter described, were of two distinct grades, termed respectively "mild" and "hard" steel. Both were products of the Bessemer converter.

All the material was rolled at the Pencoyd Iron Works, where, also, all the experiments were made.

The mild steel was rolled from ingots made by the Pittsburgh Steel Casting Company, and the hard steel from ingots made by the Lackawanna Coal and Iron Company, the former grade being such as is largely used at present for shipbuilding, and the latter grade being ordinary commercial rail steel. The mild steel had a carbon ratio varying from .11 to .15 per cent., and the hard steel .36 carbon.

A few specimens of each grade were submitted to chemical analysis, with results given hereafter.

The testing machine was the same described in "Experiments on Struts," Transactions, No. 279, April, 1884. The tensile tests, Table No. 1, were made on strips about 24 inches long, cut from bars of the sections described in the tables.

To these strips clamped plates were applied exactly 12 inches apart, and at regular intervals during elongation the distance between these clamps was measured with a callipers by the sense of touch, and read on a measuring machine to the nearest one-thousandth of an inch.

For tests of direct compression (table No. 1), specimens 12 inches long were inserted in a tube, and the space between the specimen and inside of tube was filled with fine sand, to prevent lateral deflection of the specimen under compression. For further details of this method of testing, see the Appendix to "Experiments on Struts," Transactions, April, 1884. To correct irregularities in the changes of length under stress, measurements were taken on opposite sides of the specimens, in both tensile and compressive tests, and if any difference occurred, the average of the two measurements was recorded. Table No. 1 embraces tests for tension and compression by the foregoing methods; the respective specimens, as described by number, being cut from the same bar of material. A number of tests were also made for elasticity under compression, on bars varying in length from 20 to 84 inches, as described in table No 2. In these experiments, measurements of compression were stopped when lateral flexure became noticeable, but the pressure was continued until failure ensued.

The pressures at the point of failure for the steel bars in this table are recorded in tables of strut tests Nos. 6 and 7; the various bars being indicated by numbers corresponding to each other in both tables.

Specific gravities were accurately measured of specimens from each

shape and each kind of material, and the sectional areas of test bars ascertained by the relations thus obtained between length, weight and area of section.

In tests for the elasticity of material, irregularities in constancy of ratio between changes of length and corresponding loads are frequently obtained, due either to actual differences of elasticity under differing intensities of stress, or else to imperfection of measuring appliances.

For the purpose of harmonizing such irregularities, the sums of the measured changes of length were divided by the sums of the corresponding stresses, thus obtaining correct average results. By this means the figures in column *e*, tables Nos. 1 and 2, were obtained, which signify the change of length in inches per square inch of section, and per foot of length for each 1 000 lbs. of stress below the elastic limit.

TABLES OF TRANSVERSE TESTS.

The experiments on transverse resistance were made on bars of 3 and 4 inches diameter, and on solid, flanged beams from 3 to 12 inches deep, as recorded in tables Nos. 3 and 4.

All transverse tests were made on beams supported at the ends and loaded in the middle. For this purpose, a heavy iron beam was placed on the table of the testing machine, of sufficient length to include the supports of the longest beam tested. On these supports the beam to be tested was placed, and the testing machine brought to act on the middle of the beam. A straight-edge was placed across the points of support, from which deflections were measured, so that the deflection of the supporting beam in no way affected the deflection of the specimen. The beams had no lateral support in the middle, except the little they received from the straining rods of the testing machine, which accounts for the ultimate resistance, in many instances, being so little in excess of the elastic limit.

Maximum resistance to bending was taken at the point where increase of deflection occurred without increase of load. Little value, however, is attached to the record of maximum transverse stress, as the point indicated is determined to some extent by the time occupied in applying the load. For the 10 and 12-inch beams, increase of stress was stopped when the elastic limit was positively ascertained. The tests for elastic limit were made at intervals corresponding to a varying inten-

TENSION.

No. of Expt.	Material.	Specimen from.	Elastic Limit.	Ultimate Tenacity.	Elongation in 8 in.
15	Mild steel...	7" beam bulb	37 000	65 700	23 per
"	" ...	Web of 7" bulb beam..	37 500	62 910	24.6
"	" ...	Flange of 7" bulb beam.	36 000	63 390	21.8
....	" ...	3½" angle...	38 000	57 000	25
....	Hard steel ..	¾" round	54 000	91 900	21.
....	" ..	2" angle	58 000	101 000	16.
...	" ..	2" "	58 000	109 800	15.6
10	Mild steel...	2½" angle....	44 500	66 000	....
29	Iron	Bulb of 7" bulb beam..	28 000	51 500	18 per
"	"	Web of 7" bulb beam..	28 000	51 000	16.4
"	"	Flange of 7" bulb beam .	31 000	50 900	14.
...	"	2½" angle...	30 000	46 000	....
....	"	¾" round....	34 000	51 600	22.6 p
....	"	¾" square ...	36 000	53 600	27.3
19	Mild steel...	8" I beam ..	39 000	61 440	....
16	" ...	7" I " ..	38 000	64 650	....
18	" ...	9" I " ..	41 000	67 400	21.9 p
54	" ...	12" I " ..	42 000	70 200	.5

In the last four experiments specimens for tens

TABLE NO. 1.
DIMENSIONS IN INCHES AND PRESSURES IN POUNDS.

TENSION.						COMPRESSION.			
Specimen	Elastic Limit.	Ultimate Tenacity.	Elongation in 8 Inches.	e .	E .	Elastic Limit.	e .		
bulb	37 000	65 700	23 per cent.	.000426	28 170 000	37 000	.00052	23 000	
7"									
m..	37 500	62 910	24.6 "	.000375	32 000 000	}	37 000	.00051	23 500
7"									
am.	36 000	63 390	21.8 "	.000444	27 030 000				
...	38 000	57 000	25 "	.00040	30 000 000		38 000	.00049	24 400
...	54 000	91 900	21. "	.00040	30 000 000		54 000	.00050	24 000
...	58 000	101 000	16. "	.00042	28 570 000		58 000	.....	.....
...	58 000	109 800	15.6 "	.00041	29 270 000		55 000	.00066	18 100
....	44 500	66 000	.....	.....	.....		43 000	.00057	21 000
7"									
am..	28 000	51 500	18 per cent.	.00042	28 570 000		31 000	.00047	25 100
7"									
m..	28 000	51 000	16.4 "	.00042	28 570 000	}	28 000	.00038	31 100
7"									
am.	31 000	50 900	14. "	.00041	29 270 000				
...	30 000	46 000	.....	.00044	27 270 000		28 000	.00049	24 400
...	34 000	51 600	22.6 per ct.	.000408	29 400 000		28 000	.00049	24 400
...	36 000	53 800	27.3 "	.000438	27 420 000		32 000	.00034	35 300
...	39 000	61 440	.....	.000392	30 612 000		36 000	.000793	15 100
..	38 000	64 650	.....	.000376	31 915 000		36 000	.000678	17 700
..	41 000	67 400	21.9 per ct.	.00042	28 571 000		37 000	.000553	21 700
..	42 000	70 200	.5 "	.000366	32 780 000		37 500	.00070	17 700

Experiments specimens for tension were cut from the webs, and for compression from the flanges.

COMPRESSION.

<i>e.</i>	<i>E.</i>	Greatest Pressure applied persq. in.	Perma- nent Re- duction per cent. of length.
0052	23 077 000	52 500	2.4
0051	23 530 000	52 500	2.2
0049	24 490 000	46 000	....
0050	24 000 000	59 700	.07
.....	.....	80 000	1.4
0066	18 182 000	56 000	....
0057	21 053 000	52 500	2.0
0047	25 530 000	52 500	2.1
0038	31 580 000	52 500	2.4
0049	24 490 000	48 000	....
0049	24 490 000	100 000	7.2
0034	35 300 000	90 000	10.
00793	15 132 000	71 000	4.9
00678	17 700 000	63 700	2.9
00553	21 700 000	63 700	3.2
00070	17 142 000	63 700	3.

sion from the flanges of beams.



sity of stress of 500 pounds; consequently, the given limits of elasticity may vary from the actual nearly that amount.

The calculations for co-efficients of elasticity were made from a similar basis as that previously described for longitudinal tests, that is, the sum of the measured deflections was divided by the sum of the corresponding loads, and the result taken as the average deflection per unit of load. This quantity is given in tables Nos. 3 and 4, under the head of "*d*," which means the deflection in inches per 1 000 pounds of load below the elastic limit, and for the given length and section. As the complete details of the experiments, such as the particulars of each measurement for deflection, etc., would be very diffuse, and would occupy too much space, the subject is condensed down to the form given in the tables, which are a faithful compilation of the results, and admit of direct and ready comparison between the various lengths and sections of different materials.

The following notation is adopted throughout this paper :

I = moment of inertia.

E = modulus of elasticity.

e = change of length per square inch of section, and per foot of length for each 1 000 lbs. of load.

M = bending moment.

R = modulus of maximum resistance to bending.

*R*₁ = modulus of resistance to bending at the elastic limit.

L = length of beam between supports.

W = weight.

D = distance from neutral axis to extreme fibres of beam.

d = deflection. (In the tables means the deflection for each 1 000 pounds of load.)

r = least radius of gyration.

l = length of strut.

R and *R*₁ in the tables are calculated by means of the formula for maximum fibre stress:

$$R \text{ or } R_1 = \frac{M D}{I}$$

$$E = \frac{W L^3}{48 I d}$$

TABLE No. 2.

THE EXPERIMENTS RECORDED IN THIS TABLE ARE THE DIRECT COMPRESSIONS OF BARS DESIGNATED BY CORRESPONDING NUMBERS IN TESTS OF STRUTS, TABLES NOS. 6 AND 7.

THE MEASUREMENTS OF COMPRESSION WERE STOPPED WHEN THE BARS BEGAN TO YIELD Laterally.

DIMENSIONS, IN INCHES.				WEIGHT, IN POUNDS.		
No.	Material.	Size and Shape.	Length.	Area.	<i>e</i> .	<i>E</i> .
55	Hard steel..	3" I beam.	84.6	1.76	.00044	27 272 000
28	Iron.....	" ..	84.3	1.68	.00041	29 270 000
27	Mild steel..	" ..	84.2	1.77	.00036	33 333 000
26	" ..	" ..	84.2	1.77	.00042	28 571 000
—	Iron.....	3" angle...	84.2	1.74	.00046	26 087 000
4	Mild Steel..	" ...	84.4	1.84	.00047	25 532 000
—	Iron	2½" " ...	84.4	1.19	.00060	20 000 000
10	Mild steel..	" ...	84.3	1.24	.00054	22 222 000
11	" ..	" ...	84.3	1.22	.00056	21 430 000
53	Hard steel..	1" " ...	24.	.48	.00039	30 770 000
49	" ..	1½" " ...	24.1	.61	.00053	22 640 000
21	Mild steel..	1" " ...	24.	.48	.00046	26 087 000
24	" ..	1" " ...	19.9	.47	.00052	23 077 000

} From
different
ingots.

TABLE No. 3.

TRANSVERSE TESTS OF IRON AND STEEL ROUND BARS.

DIMENSIONS IN INCHES.

LOADS IN POUNDS.

No. of Expt.	Material.	Diameter.	Area.	Length between Supports.	Ultimate Load.	Load at Elastic Limit.	R.	R ¹ .	d.	E.
1	Iron.....	3.03	7.21	60	7 850	5 000	43 100	27 500	.0409	26 640 000
2	Mild steel.....	3.015	7.14	69	8 900	6 500	57 100	41 600	.0533	31 713 000
3	Hard steel.....	3.02	7.16	60	17 000	13 000	94 300	72 100	.0405	27 261 000
4	Iron.....	3.05	7.30	69	7 450	5 000	46 100	31 000	.0537	30 804 000
5	Mild steel.....	3.03	7.21	69	8 800	6 100	55 600	38 000	.0503	32 930 000
6	Hard steel.....	3.02	7.16	69	14 975	11 600	95 500	70 200	.0618	27 008 000
7	Iron.....	3.03	7.21	69	7 700	5 000	48 600	31 600	.0493	33 631 000
8	Iron.....	4.03	12.75	69	17 900	12 500	48 300	34 000	.0205	25 820 000
9	Hard steel.....	4.04	12.81	69	39 500	29 500	105 200	78 600	.0187	28 037 000

In table No. 4 the 7-inch steel bulb beams Nos. 15 and 16 were cut from the same original bar, as were also the iron beams Nos. 29 and 30. The behavior of these beams under stress was peculiar, and requires explanation. This section of beam, if straightened hot, will curve in cooling, owing to the unequal cooling of the unequal flanges. The bulb remains on the concave side; consequently, if straightened cold, the flanges are strained, the bulb in tension and the flange in compression. The four beams referred to were straightened cold; all other beams tested were curved hot when the section required it, and tested in the condition they left the rolls. The particulars of the deflections are given for these four beams on the next page, showing how irregularly they acted.

ELASTICITY OF STEEL.

The elasticity of either steel or iron is so variable and uncertain, that it is difficult to assign a definite value to any particular material, except by taking the averages of numerous experiments. Carefully conducted experiments on iron with the Government machine at Watertown yielded for tension, elastic moduli varying from 24 to over 33 millions of pounds, an average of some twenty experiments was 28 234 000 pounds. For compression the moduli varied from 26 500 000 to 35 300 000; an average of twenty tests was 29 000 000 pounds. Transverse tests on round bars with the same machine gave elastic moduli varying from 20 to over 30 millions, with an average for twelve tests of 25 360 000; and for rolled I beams moduli varying from 26 to 36 millions were obtained, with an average for twenty-five tests of 31 000 000 pounds. The general averages of elasticity obtained from the Pencoyd experiments, as previously recorded, are summarized in table No. 5. As but few experiments were made on hard steel, the comparison instituted is not so just as that made between the mild steel and iron.

It seems probable that the elasticity of the different materials is practically uniform. The steel may stretch less than the iron in tension, but it is more certain that the steel shortens the most under compression. Transversely, if any practical difference at all exists, the advantage in stiffness probably belongs to steel. But the elasticity of both metals is so close and uncertain that these averages might be considerably modified one way or the other by further experiments.

TAB

TRANSVERSE TESTS OF IRON

DIMENSIONS IN INCHES.

The figure for bulb beams denotes the

No of Expr't.	Material.	Kind of Beam.	Area.	Moment of Inertia.	Distance from Neu- tral Axis to Extreme Fibre.	Len betw Supp
10	Mild steel..	3" I beam.	1.77	2.76	1.5	
11	"	" " "	1.77	2.76	1.5	
12	"	5" I " "	3.34	12.	2.78	1
13	"	5" I " "	3.34	12.	2.78	1
14	"	6" I " "	4.19	22.	3.35	
15	"	7" I " "	5.42	37.6	3.8	
16	"	7" I " "	5.42	37.6	3.8	
17	"	9" I " "	7.18	84.8	5.0	2
18	"	9" I " "	6.9	82.9	5.0	2
19	"	8" I " "	6.72	70.2	4.0	2
20	"	" " "	6.74	70.3	4.0	2
21	"	" " "	6.72	70.2	4.0	1
22	"	" " "	6.72	70.2	4.0	
23	Hard steel..	3" I " "	1.76	2.74	1.5	
24	Iron.....	" " "	1.68	2.63	1.5	
25	"	" " "	1.68	2.63	1.5	
26	"	5" I " "	3.51	12.3	2.78	1
27	"	5" I " "	3.34	12.0	2.78	1
28	"	6" I " "	4.16	21.9	3.35	
29	"	7" I " "	5.35	37.2	3.8	
30	"	7" I " "	5.35	37.2	3.8	
31	"	9" I " "	8.18	91.6	5.0	2
32	"	9" I " "	8.18	91.6	5.0	2
33	"	8" I " "	6.58	69.4	4.0	2
34	"	" " "	6.65	69.9	4.0	1
35	"	" " "	6.7	70.1	4.0	1
36	"	" " "	6.54	69.2	4.0	

TABLE No. 4.

TRANSVERSE TESTS OF IRON AND STEEL FLANGED BEAMS.

ES.

LOADS IN POUNDS.

bulb beams denotes the position of flange when the beam was tested.

Moment of Inertia.	Distance from Neutral Axis to Extreme Fibre.	Length between Supports.	Ultimate Load.	Load at Elastic Limit.	R.	R. ₁	d.	
2.76	1.5	59	5 500	5 000	45 200	41 100	.0513	30
2.76	1.5	39	8 300	7 500	45 100	40 800	.0183	28
12.	2.78	108	8 800	8 000	55 000	50 000	.0789	27
12.	2.78	108	8 400	7 500	52 500	46 900	.0858	28
22.	3.35	96	14 860	14 000	54 300	51 200	.0340	28
37.6	3.8	69	34 000	27 000	59 300	47 100	.0097	18
37.6	3.8	69	34 000	27 000	59 300	47 100	.0079	28
84.8	5.0	240	14 500	13 000	51 300	46 000	.1135	28
82.9	5.0	240	13 500	11 000	48 800	39 800	.1150	38
70.2	4.0	240	13 000	11 000	44 400	37 600	.1420	28
70.3	4.0	240	12 930	11 000	44 100	37 500	.1410	28
70.2	4.0	144	19 480	16 000	39 900	32 800	.0283	38
70.2	4.0	96	31 300	29 500	42 800	40 300	.0110	28
2.74	1.5	39	11 500	10 000	62 000	54 300	.0170	28
2.63	1.5	39	7 500	6 000	42 300	33 900	.0213	28
2.63	1.5	59	5 000	4 500	42 700	38 400	.0573	28
12.3	2.78	108	7 440	6 500	45 400	39 700	.0771	28
12.0	2.78	108	7 310	6 500	45 700	40 600	.0833	28
21.9	3.35	96	13 440	12 500	49 300	45 900	.0339	28
37.2	3.8	69	26 000	20 000	45 800	35 800	.0096	18
37.2	3.8	69	28 000	20 000	49 300	35 200	.0080	28
91.6	5.0	228	13 310	11 000	41 400	34 200	.1030	28
91.6	5.0	228	13 640	10 000	42 400	31 400	.0930	28
69.4	4.0	240	10 630	9 500	36 800	32 800	.148	28
69.9	4.0	240	10 940	9 000	37 500	30 900	.153	28
70.1	4.0	144	19 800	17 000	40 700	34 900	.037	28
69.2	4.0	96	29 100	25 500	40 400	35 400	.0115	28

POUNDS.

ted.

d.	E.	
.0513	30 890 000	
.0183	25 011 000	
.0789	27 718 000	} Rolled from same ingot.
.0858	25 489 000	
.0340	23 692 000	
.0097	18 765 000	} From same ingot.
.0079	23 040 000	
.1135	29 923 000	
.1150	30 209 000	
.1420	28 889 000	} Nos. 19, 21 and 22 from same ingot.
.1410	29 055 000	
.0283	31 313 000	
.0110	23 869 000	
.0170	26 982 000	
.0213	22 310 000	
.0573	28 720 000	
.0771	27 674 000	
.0833	26 255 000	
.0339	24 827 000	
.0096	19 164 000	} From same pile.
.0080	22 997 000	
.1030	26 172 000	
.0930	28 988 000	
.148	28 039 000	
.153	26 929 000	
.037	23 984 000	
.0115	23 162 000	

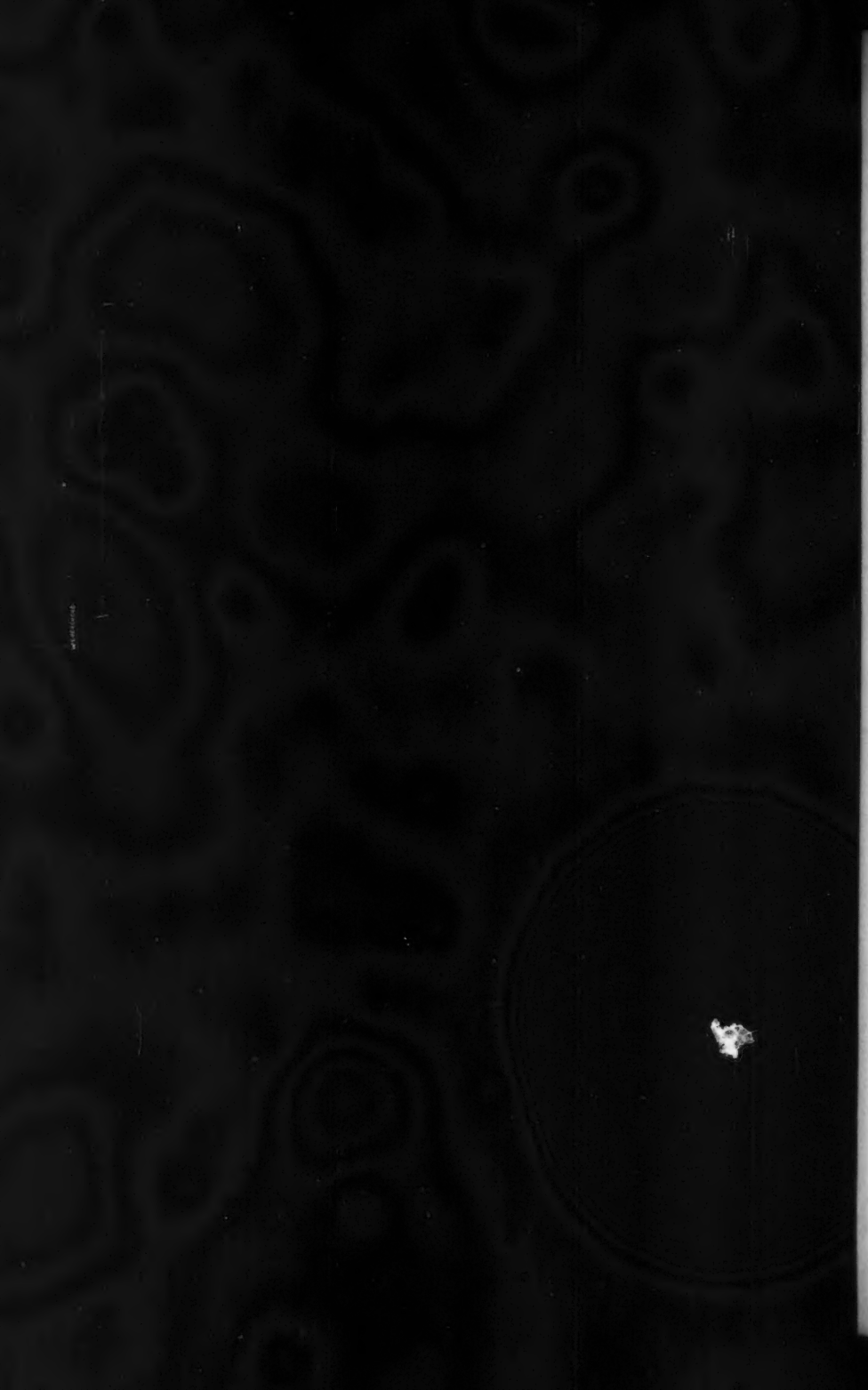





TABLE No. 4—(C)
TRANSVERSE TESTS OF STEEL

DIMENSIONS IN INCHES.

No. of Exprt.	Material.	Size of Beam.	Area.	Moment of Inertia.	Length between Supports.	I
37	Mild steel..	10-inch  beam.	9.2	150.5	156	
38	"	"	"	"	168	
39	"	"	"	"	180	
40	"	"	"	"	192	
The above four beams were rolled						
41	Iron.....	10-inch  beam.	9.24	149.5	156	
42	"	"	9.24	149.5	168	
43	"	"	9.10	149.1	180	
44	"	"	9.17	148.41	192	
Numbers 41 and 42 were rolled f						
45	Mild steel..	12-inch  beam.	11.59	264.7	240	
46	"	"	11.72	267.6	240	
47	"	"	11.99	273.8	228	
48	"	"	11.55	263.7	216	
49	"	"	11.24	256.7	204	
50	"	"	11.29	257.8	192	
51	"	"	11.50	262.6	192	
52	"	"	11.49	262.4	180	
53	"	"	11.56	264.0	168	
54	"	"	11.46	261.7	156	
55	Iron	"	16.21	357.0	240	
56	"	"	11.73	267.8	228	
57	"	"	16.42	361.6	216	
58	"	"	12.20	278.6	204	
59	"	"	11.71	267.4	180	
60	"	"	12.27	280.2	168	

The moment of inertia was calculated for each section, in accordance with the method of least squares, on some beams than on others having nearly the same sectional areas, and the moments of inertia and sectional areas for different beams.

TABLE No. 4—(Continued).

VERSE TESTS OF STEEL AND IRON BEAMS.

LOADS IN POUNDS.

Moment of Inertia.	Length between Supports.	Load at Elastic Limit.	Def'n at Elastic Limit.	Set at Elastic Limit.	<i>d.</i>	<i>R.</i> ₁	<i>R.</i> ₂
150.5	156	22 500	.4375	.0165	.0191	35 000	27 500
"	168	21 000	.502	.021	.0231	35 200	28 400
"	180	19 500	.584	.029	.0297	35 000	27 100
"	192	18 000	.616	.017	.0336	34 400	29 100
Four beams were rolled from the same ingot.							
149.5	156	16 000	.297	.006	.0185	25 000	28 500
149.5	168	15 000	.3655	.0185	.0239	25 300	27 600
149.1	180	14 000	.408	.0145	.0288	25 400	28 100
148.41	192	12 500	.449	.0145	.0345	24 300	28 700
41 and 42 were rolled from the same pile.							
264.7	240	24 500	.915	.0255	.0366	33 400	29 700
267.6	240	24 200	.869	.0205	.0350	32 500	30 700
273.8	228	22 000	.6975	.....	.0305	27 500	29 500
263.7	216	29 000	.8065	.034	.0273	35 600	29 100
256.7	204	27 000	.65	.....	.0228	32 100	30 200
257.8	192	34 000	.6675	.026	.0189	38 000	30 000
262.6	192	34 000	.6765	.0415	.0189	37 300	29 700
262.4	180	36 700	.601	.0375	.0164	37 700	28 200
264.0	168	38 000	.5205	.0335	.0135	36 300	27 700
261.7	156	43 000	.4655	.014	.0105	38 400	28 700
357.0	240	22 000	.6605	.037	.0290	22 200	27 800
267.8	228	20 500	.703	.042	.0314	26 200	29 300
361.6	216	25 000	.568	...	.0220	22 400	26 300
278.6	204	23 000	.5675	.035	.0235	25 300	27 000
267.4	180	23 500	.3985	.008	.0168	23 700	27 000
280.2	168	25 500	.3395	.009	.0131	22 900	26 900



Each section, in accordance with actual measurements. The flanges were of the same sectional areas, which accounts for some seeming inconsistencies between the beams.

	<i>E.</i>
000	27 515 000
200	28 414 000
000	27 182 000
400	29 160 000
000	28 597 000
300	27 647 000
400	28 138 000
300	28 799 000
400	29 727 000
500	30 749 000
500	29 568 000
500	29 164 000
100	30 219 000
000	30 030 000
300	29 709 000
700	28 234 000
300	27 717 000
100	28 784 000
200	27 818 000
200	29 364 000
400	26 392 000
300	27 015 000
700	27 046 000
900	26 912 000



anges were wider
tencies between



7" STEEL BEAMS, FROM SAME ORIGINAL BEAM.

No. 15.  BULB UP.			No. 16.  BULB DOWN.		
Pressure, in Lbs.	Deflection, in Inches.	Permanent Set, in Ins.	Pressure, in Lbs.	Deflection, in Inches.	Permanent Set, in Ins.
5 000	.043	.0	5 000	.040	.0
10 000	.084	.002	10 000	.078	.0
15 000	.129	.015	15 000	.113	.0
20 000	.187	.040	20 000	.158	.001
22 000	.217	.055	22 000	.169	.006
24 000	.242	.068	24 000	.191	.010
26 000	.276	.089	26 000	.211	.017
28 000	.308	.117	28 000	.240	.038
30 000	.378	.176	30 000	.305	.098
32 000	.543	.328	32 000	.540	.319
34 000	Ultimate.		34 000	Ultimate.	

7" IRON BEAMS, CUT FROM SAME ORIGINAL BAR.

No. 29.  BULB UP.			No. 30.  BULB DOWN.		
Pressure, in Lbs.	Deflection, in Inches.	Permanent Set, in Ins.	Pressure, in Lbs.	Deflection, in Inches.	Permanent Set, in Ins.
5 000	.055	.0	5 000	.039	.0
10 000	.094	.0	10 000	.080	.0
15 000	.139	.008	15 000	.118	.0
20 000	.215	.052	20 000	.200	.042
22 000	.239	.061	22 000	.221	.050
24 000	.319	.122	24 000	.230	.068
26 000	Ultimate.		26 000	.539	.362
			28 000	Ultimate.	

EFFICIENCY OF STEEL BEAMS.

The foregoing experiments show that the elastic limits for tensile and compressive stress for each particular grade of steel respectively, are nearly equal per unit of section, and, as might be expected, the transverse resistance is approximately proportionate to the longitudinal resistance. The average results of all tests for elastic limit and transverse resistance are summarized in table No. 5, which tend to prove that the strength of the material, as indicated by tensile test, will serve as a comparative measure of the absolute strength of beams of iron or either grade of steel. But as the transverse elasticity of the different materials is practically alike, beams of iron or either grade of steel, and of the same lengths and sections, will deflect alike under equal loads below the elastic limit of iron.

TABLE No. 5.

SUMMARY OF EXPERIMENTS ON THE STRENGTH AND ELASTICITY OF IRON AND STEEL.

POUNDS PER SQUARE INCH.

	Hard Steel, 36 Carbon.	Mild Steel, 12 Carbon.	Iron.
Ultimate tensile resistance.....	100 900	63 400	50 800
Tensile resistance at the elastic limit.	56 700	39 400	31 200
Compressive resistance at the elastic limit.....	55 700	36 800	29 400
Ultimate elongation per cent. in 8 inches.	17.5	23.6	19.7
R.....	80 200	52 900	44 800
R ₁	54 300	39 450	30 960
E in tension { least.....	28 570 000	27 030 000	27 270 000
{ greatest.....	30 000 000	32 780 000	29 400 000
{ average.....	29 280 000	30 135 000	28 416 000
E in compression { least.....	18 182 000	15 132 000	20 000 000
{ greatest.....	30 770 000	24 490 000	35 300 000
{ average.....	24 570 000	20 478 000	27 093 000
E in bending { least.....	27 008 000	18 765 000	19 164 000
{ greatest.....	28 037 000	32 930 000	33 631 000
{ average.....	27 163 000	29 758 000	27 663 000

TESTS OF STRUTS.

The experiments on the resistance of struts were made on flat-ended angle and beam sections. Tables Nos. 6 and 7.

The bars were prepared in the same manner and the experiments conducted precisely as described in the paper on "Wrought-Iron Struts," Transactions for April, 1884, which can be referred to for more complete details of the methods adopted, and the basis on which the calculations of the tables have been made.

Referring to table No. 6, tests of mild steel, the 3-inch I beams, Nos. 26 and 27, were not rolled from the same ingot. No. 26 was known to be from a Bessemer ingot, very soft steel, probably not exceeding .10 carbon. The record of No. 27 is not definitely known; it may have been higher in carbon than No. 26. The resistance of No. 26, however, was abnormal, as an iron beam of the same length and section exceeded it in resistance, as exhibited near the foot of table No. 6.

The three angle struts, Nos. 10, 22 and 24, were cut from the same original bar; their resistance exceeded that of the other mild steel struts, which induced a suspicion that the steel was harder than the average. A piece from one of these bars, when chilled from a red heat in water of 80° F., cracked when bent 90°. A tensile test of the same (marked No. 10 on table No. 1) showed an ultimate tenacity of 66 000 pounds and elastic limit of 44 500 pounds per square inch; submitted to chemical analysis, it proved to contain .15 per cent. of carbon.

The experiments on direct tension and compression prove that the elastic limits of steel of any particular grade are practically equal per unit of section, for either direction of stress.

A similar equality is known to obtain approximately with iron. Consequently, for the shortest struts, in which failure results entirely, or nearly so, from the effects of direct compression, the tensile resistance of either material will serve as a comparative measure of the strut resistance. The limited capacity of the testing machine prevented experiments on struts of this class of any substantial magnitude; but single experiments on small specimens having a ratio of length over radius of gyration of 20, gave resistances of about 50 000, 70 000 and 100 000 pounds per square inch for iron, mild steel and hard steel respectively, which are values roughly approximate to the ultimate tenacities of the materials. But as struts increase in length, the lateral stiffness of the

material becomes a factor of increasing importance in determining the stability of the strut.

It has been shown that the transverse elasticity of either grade of steel does not, on an average, vary much from that of iron.

The tendency, therefore, will be for struts of steel and iron to approximate towards equality of resistance as the lengths are increased. The mild steel will be the first to fall to equality with iron, and the experiments show that practical equality between the strut resistances of these two metals will be reached when the ratio of length to least radius of gyration is about 200 to 1. At this point the hard steel has still an advantage in strength over the other materials of about 22 per cent.

It is altogether probable that the strut resistance of hard steel would fall to practical equality with iron at some higher but unknown ratio of length to section, a ratio, however, which would be beyond the bounds of practice. The appended table gives ultimate strut resistances for the mild and hard steels, for ratios of length over radius of gyration, varying from 20 up to 300. For the purpose of comparison, the resistance of angle iron struts is inserted, which is the same shape of section as the steel experimented upon, and is taken from table No. 9, page 116, Transactions for April, 1884.

The diagrams, Nos. 6 and 7, Plates XXXV and XXXVI, are graphical exhibits of the tests of mild and hard steel. The numbers on the diagrams indicate the test referred to by corresponding numbers on tables Nos. 6 and 7.

Diagram No. 8, Plate XXXVII, represents the resistance curves of iron and the two grades of steel, the curve for iron being taken from diagram No. 1 for flat-ended angle struts in Transactions, April, 1884.

It is probable that the two grades of steel which formed the subjects of the experiments will prove the extremes from soft to hard that will be used either as beams or struts, and it is a reasonable inference that intermediate grades of steel will prove intermediate in resistance between these extremes in the ratio of the carbon percentages.

TABLE N
MILD STEEL—FLAT—

No.	Shape.	Size, in Inches.	Length, L, in Inches.	Area, in Square Inches.	Ultimate Resist- ance, Lbs.	Ultimate Resist- ance, Lbs. per Sq. Inch.	$\frac{L}{r}$	The upper flange The figures in parentheses	
1	Angle	3 x 3 x $\frac{1}{16}$	182.	1.9	15 020	7 895	303	5 000 .19	10 000 .31
2	"	"	169.4	1.9	17 260	9 084	282	10 000 .12	15 000 .50
3	"	"	132.1	1.8	25 615	14 230	220	5 000 .19	10 000 .28
4	"	"	84.4	1.84	46 800	25 434	141	18 400 .00	27 600 .02
5	"	3½ x 3½ x $\frac{1}{16}$	168.5	2.18	20 765	9 525	241	5 000 .28	10 000 .56
6	"	"	133.5	2.24	47 290	21 101	191	5 000 .09	10 000 .13
7	"	"	154.5	2.24	32 080	14 321	221	5 000 .00	10 000 .10
8	"	3½ x 3½ x $\frac{1}{16}$	182.6	2.25	27 820	12 364	261	5 000 .00	10 000 .06
9	"	2½ x 2½ x $\frac{1}{16}$	182.	1.86	10 790	5 800	324	5 000 .31	10 000 1.16
10	"	2½ x 2½ x $\frac{1}{16}$	84.2	1.24	31 700	25 560	169	4 960 .02	9 920 .02
11	"	"	84.3	1.22	28 275	23 176	169	4 880 .00	9 760 .03
12	"	"	42.3	1.24	42 710	34 443	85	6 200 .00	12 400 .01
13	"	"	41.4	1.24	42 640	34 390	83	6 200 .00	12 400 .01
14	"	"	24.1	1.22	.....	.....	20	.....	.....
15	"	2 x 2 x $\frac{1}{16}$	24.3	.98	39 945	40 803	61	4 900 .00	29 000 .01
16	"	"	24.1	.97	42 820	44 098	60	4 900 .00	9 700 .01
17	"	1½ x 1½ x $\frac{1}{16}$	18.1	.74	32 710	44 382	58	3 600 .00	25 800 .01
18	"	"	16.6	.74	29 735	40 400	54	3 700 .00	25 800 .01
19	"	1½ x 1½ x $\frac{1}{16}$	10.6	.61	28 875	47 336	41	.....	.....
20	"	"	7.9	.61	27 445	45 741	30	.....	.....
21	"	1 x 1 x $\frac{1}{16}$	24.	.60	19 175	31 958	125	5 000 .02	10 000 .05
22	"	1 x 1 x $\frac{1}{16}$	23.9	.48	17 235	35 906	120	5 000 .00	10 000 .00
23	"	1 x 1 x $\frac{1}{16}$	20.1	.59	19 635	33 280	105	5 000 .02	10 000 .02
24	"	1 x 1½ x $\frac{1}{16}$	19.9	.47	19 480	41 447	100	5 000 .01	10 000 .02
25	"	1 x 1 x $\frac{1}{16}$	4.	.45	32 710	72 688	20	.....	.....
26	I	3" beam	84.2	1.77	35 000	19 780	159	3 540 .00	8 850 .00
27	"	"	84.2	1.77	44 900	25 360	159	3 540 .00	28 320 .00
28	"	Iron }	84.3	1.68	39 575	23 550	159	8 400 .01	10 800 .00
60	Angle	3½ x 3½ x $\frac{1}{16}$	145.	2.06	25 210	12 238	207	5 000 .22	10 000 .30
61	"	"	139.2	2.06	38 800	18 835	199	5 000 .06	10 000 .10
62	"	2½ x 2½ x $\frac{1}{16}$	89.2	1.45	29 580	20 400	198	5 000 .03	10 000 .00

TABLE No. 6.

MILD STEEL—FLAT-ENDED STRUTS.

Distance per Inch.	$\frac{l}{r}$	The upper figures represent pressures in lbs. The figures below are the lateral deflections in inches.							Permanent Set.	
895	303	5 000 .19	10 000 .31	15 000 1.03	.....	.....	.....	.....	.56	
084	282	10 000 .12	15 000 .50	.....	.....	.....	.....	.....	.12	
230	220	5 000 .19	10 000 .28	15 000 .44	20 000 .62	25 000 1.03	.....	.....	.50	
434	141	18 400 .00	27 600 .02	36 800 .04	46 000 .20	46 800 1.19	.....	.....
525	241	5 000 .28	10 000 .56	15 000 .78	20 000 1.37	.....	.....	.....	.37	
101	191	5 000 .09	10 000 .13	25 000 .13	30 000 .16	31 000 .19	40 000 .22	45 000 .38	1.37	
321	221	5 000 .00	10 000 .10	15 000 .16	20 000 .22	25 000 .38	30 000 .66	.....	.56	
354	261	5 000 .00	10 000 .06	15 000 .10	20 000 .13	25 000 .25	.....	.....	.81	
800	324	5 000 .31	10 000 1.16	.....	.....	.....	.....	.....	.00	
560	169	4 960 .02	9 920 .02	14 880 .02	19 840 .04	24 800 .04	29 760 .10	31 700 .20	.....	{ Same No
176	169	4 880 .00	9 760 .03	14 640 .07	19 520 .12	24 400 .19	28 200 1.94	.....	
443	85	6 200 .00	12 400 .01	18 600 .02	24 800 .03	31 000 .05	37 200 .08	.....	
390	83	6 200 .00	12 400 .01	18 600 .03	24 800 .03	31 000 .04	37 200 .08	.....	
.....	20	.....	.....	.....	.....	.....	.....	.....	.....	No fail
803	61	4 900 .00	29 000 .01	34 000 .02	39 000 .06	.....	.....	.....
098	60	4 900 .00	9 700 .01	29 000 .02	38 000 .03	.....	.....	.....
382	58	3 600 .00	25 800 .01	29 500 .02	.....	.....	.....	.....
400	54	3 700 .00	25 800 .01	29 500 .07	.....	.....	.....	.....
336	41	.....	.....	.....	.....	.....	.....	.....
741	30	.....	.....	.....	.....	.....	.....	.....
838	125	5 000 .02	10 000 .03	15 000 .04	.....	.....	.....	.....	.56	
906	120	5 000 .00	10 000 .01	15 000 .01	.....	.....	.....	.....	.56	{ Same du
280	105	5 000 .02	10 000 .02	15 000 .03	.....	.....	.....	.....	.50	
447	100	5 000 .01	10 000 .02	15 000 .03	.....	.....	.....	.....	.56	
588	20	.....	.....	.....	.....	.....	.....	.....	.....	{ Same du
780	159	3 540 .00	8 850 .01	14 160 .05	21 240 .09	28 320 .15	35 000 1.44	.....	.....	{ Roll in
960	159	3 540 .00	28 320 .01	35 400 .02	42 480 .15	44 900 2.06	.....	.....	.....
550	159	8 400 .01	10 800 .02	13 440 .03	20 160 .05	26 880 .07	33 600 .10	.....	.....
238	207	5 000 .22	10 000 .34	15 000 .47	20 000 .60	25 000 1.16	.....	.....	.....	{ 60 ar ba
835	199	5 000 .06	10 000 .16	15 000 .22	20 000 .25	25 000 .40	30 000 .50	35 000 .65	.....
400	198	5 000 .03	10 000 .06	15 000 .09	20 000 .12	25 000 .16	.....	.....	.....

ment .	REMARKS.
6 2 0	
7 7 6 1 0	
.....	{ Same as No. 10 on table No. 1.
.....	No failure with 50 000 lbs.
6 6 0 6	
.....	{ Same bar as No. 10 re- duced in section.
.....	{ Same bar as No. 10 re- duced in section.
.....	{ Rolled from different ingots.
.....	{ 60 and 61 cut from same bar.



TABLE NO.
HARD STEEL—FLAT—

No.	Shape.	Size, in Inches.	Length, in Inches.	Area, in Square Inches.	Ultimate Resist- ance, Lbs.	Ultimate Resist- ance, Lbs. per Sq. Inch.	$\frac{t}{r}$	The The in
30	Angle.	$3\frac{1}{2} \times 3\frac{1}{2} \times \frac{3}{8}$	155.	2.42	39 200	16 198	221	5 000 .00
31	"	$3\frac{1}{2} \times 3\frac{1}{2} \times \frac{1}{2}$	176.5	2.28	25 125	11 018	252	5 000 .37
32	"	"	169.	2.2	32 015	14 552	239	5 000 .22
33	"	$3\frac{1}{4} \times 3\frac{1}{4} \times \frac{1}{2}$	176.5	2.2	23 975	10 900	271	5 000 .00
34	"	$3 \times 2\frac{1}{2} \times \frac{3}{8}$	181.2	1.9	17 960	9 421	302	5 000 .06
35	"	$3 \times 3 \times \frac{1}{2}$	169.6	2.04	22 200	10 882	283	5 000 .16
36	"	$3 \times 3 \times \frac{3}{4}$	84.4	1.42	49 580	34 916	140	7 100 .01
37	"	"	84.3	1.42	44 680	31 465	140	7 100 .01
38	"	"	78.2	1.42	47 525	33 468	130	7 100 .02
39	"	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{8}$	181.2	1.86	14 460	7 774	322	5 000 .15
40	"	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{4}$	84.6	1.69	42 200	24 970	169	5 000 .03
41	"	$2\frac{1}{4} \times 2\frac{1}{4} \times \frac{3}{8}$	84.7	1.53	34 460	22 523	188	5 000 .03
42	"	$2 \times 2 \times \frac{3}{8}$	83.6	1.7	20 010	18 700	209	4 280 .00
43	"	$2 \times 2 \times \frac{1}{2}$	84.3	1.00	20 815	20 815	211	4 000 .00
44	"	"	42.3	1.00	43 610	43 610	106	5 000 .00
45	"	"	42.1	1.00	46 010	46 010	105	5 000 .00
46	"	$1\frac{1}{2} \times 1\frac{1}{2} \times \frac{1}{4}$	23.9	.71	40 475	53 246	77	
47	"	"	24.1	.76	41 310	54 355	78	
48	"	$1\frac{3}{4} \times 1\frac{3}{4} \times \frac{1}{4}$	19.	.68	39 960	58 764	64	
49	"	$1\frac{1}{2} \times 1\frac{1}{2} \times \frac{1}{2}$	24.1	.61	32 940	54 000	93	5 000 .02
50	"	"	12.1	.62	37 147	59 903	46	
51	"	"	11.9	.62	38 535	62 153	46	
52	"	"	7.9	.60	44 610	74 350	30	
53	"	$1 \times 1 \times \frac{1}{4}$	24.	.48	19 930	41 520	120	5 000 .01
54	"	"	4.	.45	48 250	107 222	20	
55	I	3" beam	84.4	1.76	51 000	29 000	159	3 500 .00

TABLE No. 7.
HARD STEEL—FLAT-ENDED STRUTS.

Ultimate Resistance. Lbs.	Ultimate Resistance. Lbs. per Sq. Inch.	$\frac{l}{r}$	The upper figures represent pressures in lbs. The figures below are the lateral deflections in inches.							Perma- nent Set.
39 200	16 198	221	5 000 .00	20 000 .03	25 000 .06	30 000 .13	35 000 .16	.....	.12
25 125	11 018	252	5 000 .37	10 000 .56	15 000 .72	25 000 1.60	.....	.....	.00
32 015	14 552	239	5 000 .22	10 000 .28	15 000 .34	20 000 .37	25 000 .47	30 000 .63	.19	
23 975	10 900	271	5 000 .00	10 000 .09	15 000 .25	20 000 .50	.....	.....	.00
17 960	9 421	302	5 000 .06	10 000 .13	15 000 .28	.....	.....	.....	.00
22 200	10 882	283	5 000 .16	10 000 .16	15 000 .16	20 000 .94	.....	.....	.10
49 580	34 916	140	7 100 .01	14 200 .02	21 300 .03	28 400 .05	35 500 .09	42 600 .18		
44 680	31 465	140	7 100 .01	14 200 .01	21 300 .02	28 400 .05	35 500 .09	42 600 .24		
47 525	33 468	130	7 100 .02	14 200 .07	21 300 .12	28 400 .17	35 500 .24	42 600 .39		
14 460	7 774	322	5 000 .19	10 000 .28	.....	.....	.....	.....	.06
42 200	24 970	169	5 000 .09	10 000 .12	15 000 .15	25 000 .21	35 000 .34	40 000 .46	.66	
34 460	22 523	188	5 000 .03	10 000 .06	15 000 .09	20 000 .12	25 000 .15	30 000 .25	.41	
20 010	18 700	209	4 280 .00	8 560 .01	12 840 .03	17 120 .09	.....	.....
20 815	20 815	211	4 000 .00	8 000 .01	12 000 .04	16 000 .10	20 000 .28	.....	
43 610	43 610	106	5 000 .00	10 000 .01	15 000 .02	25 000 .03	35 000 .06	40 000 .08		
46 010	46 010	105	5 000 .00	10 000 .01	15 000 .02	25 000 .03	35 000 .03	45 000 .04		
40 475	53 246	77								
41 310	54 355	78								
39 960	58 764	64								
32 940	54 000	93	5 000 .01	10 000 .01	15 000 .01	25 000 .02	30 000 .03	.....	.40
37 140	59 903	46						.....	
38 535	62 163	46								
44 610	74 350	30								
19 930	41 520	120	5 000 .01	10 000 .02	15 000 .04	.....	.....	.....	.28
48 250	107 222	20								
51 000	29 000	159	3 500 .00	21 120 .01	28 160 .02	35 200 .03	42 200 .04	50 000 .09	{ From No. 2	

Per- ma- nent Set.	REMARKS.
.12	
.00	
.19	
.00	
.00	
.10	
.06	
.66	
.41	
.40	
.28	
.. {	From same bar as No. 23, table No. 4.



FLAT-ENDED STRUTS.









Of angle section.

ULTIMATE RESISTANCE IN POUNDS PER SQUARE INCH OF SECTION.

Length Divided by Least Radius of Gyration.	Iron.	Mild Steel.	Hard Steel.
20	49 000	72 000	100 000
30		51 000	74 000
40	40 000	46 000	65 000
50		43 000	61 000
60	35 000	41 000	58 000
70		39 000	56 000
80	32 000	38 000	54 000
90		36 500	51 000
100	29 000	35 000	47 000
110		33 500	43 500
120	26 000	31 500	40 000
130		29 000	36 500
140	23 500	27 000	33 500
150		25 000	30 800
160	21 000	23 000	28 300
170		21 000	26 000
180	19 000	19 500	23 800
190		18 000	21 800
200	16 500	16 500	20 000
210		15 200	18 400
220	14 000	14 000	16 900
230		13 000	15 400
240	12 000	12 000	14 000
250		11 100	12 800
260	10 500	10 300	11 800
270		9 600	11 000
280	9 000	9 000	10 200
290		8 400	9 500
300	7 500	7 900	9 000

ANALYSES OF STEEL.

THE NUMBERS OF EXPERIMENTS AND TABLES REFER TO CORRESPONDING NUMBERS IN PREVIOUS TABLES, WHERE PHYSICAL TESTS OF THE SAME SPECIMENS ARE RECORDED.

No. of Experiment.	No. of Table.	Specimen.	Carbon.	Silicon.	Manganese.	Specific Gravity.
15	1 and 4	7" 	.15	.038	.65	{ bulb = 7.856 web = 7.775
20	4	8" 	.16	.028	.67	
19	1 and 4	"	.11	.058	.49	{ flange = 7.834 web = 7.943
18	"	9" 	.16	.034	.63	{ bulb = 7.864 web = 7.827
12	4	5" 	.15	.034	.69	7.84
14	"	6" 	.15	.036	.69	7.855
Same steel } as 3 and 6 }	3	6" 	.35	.074	.85	7.8
37 to 40	4	10" 	.12	.030	.65	7.808
54	4	12" 	.15	.054	.70	{ flange = 7.848 web = 7.914
60-61	6	3½" angle	.19	.027	.72	7.84
43	7	2" "	.36	.076	1.12	7.84
6 } 7 } 62 }	6	3½" "	.12	.041	.42	7.86
10 } 22 } 24 }	6	2½" "	.15	.04	.64	
Mild steel ingot						= 7.792

LBS PER
SQ. INCH

PLATE XXV
TRANS. A.M. SOC. CIV. ENGRS
VOL. XIII NO. CCLXXXVI
CHRISTIE ON
STRUCTURAL STEEL

70000

625

60000

50000

40000

30000

20000

10000

0

20

FLAT ENDED STRUTS

12 CARBON STEEL (MILD)

⊕ ANGLES
+ BEAMS

⊙ 15 CARBON STEEL

N° 9 NOT ON THE DIAGRAM.

N° 6.

LENGTH DIVIDED BY LEAST RADIUS OF GYRATION

300

280

260

240

220

200

180

160

140

120

100

80

60

40

20

0

24

23

22

21

20

19

18

17

16

15

14

13

12

11

10

9

8

7

6

5

4

3

2

1

0

-1

-2

-3

-4

-5

-6

-7

-8

-9

-10

-11

-12

-13

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-99

-100



LIBS. PER
SQ. INCH

PLATE XXXVI
TRANS. AM. SOC. CIV. ENGRS
VOL. XIII NO. CCLXXXVI
CHRISTIE ON
STRUCTURAL STEEL

FLAT ENDED STRUTS .36 CARBON STEEL (HARD)

⊙ ANGLES
+ BEAMS

NO. 39 & 54 NOT ON THE DIAGRAM.

Nº 7.

LENGTH DIVIDED BY LEAST RADIUS OF GYRATION

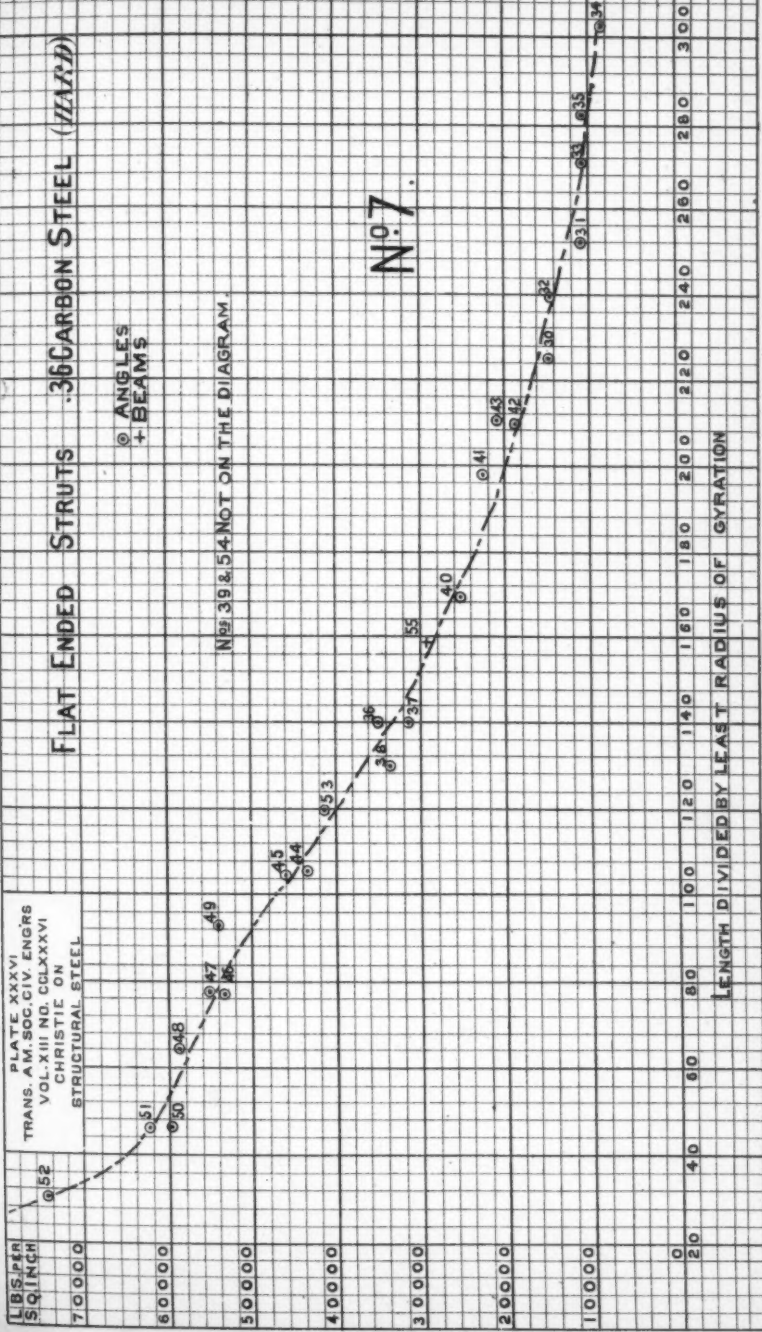




PLATE XXXVII
TRANS. AM. SOC. CIV. ENGRS
VOL. XIII NO. CCLXXXVI
CHRISTIE ON
STRUCTURAL STEEL

COMPARATIVE RESISTANCE OF IRON AND STEEL FLAT ENDED STRUTS.

Nº 8.

